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A comparison of sea surface temperatures from the AATSR and AIRS instruments

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A comparison of sea surface temperatures from the Advanced Along-track Scanning Radiometer and the Atmospheric Infrared Sounder instruments

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Abstract

Access to Advanced Infra-Red Sounder (AIRS) sea surface temperature (SST) data provides further validation possibilities for the Advanced Along-Track Scanning Radiometer (AATSR) SST data. Three months in 2006, January, April and June, are selected for this validation and the mean, monthly, night-time SST fields inferred from two AIRS channels, 1231cm^{-1} and 2616cm^{-1}, are subtracted from the AATSR dual view, three channel, night-time SST. The statistics collected from this show that AATSR skin SST minus AIRS SST gives a positive bias, of 0.6K, meaning AIRS gives cooler SST's than AATSR. This is repeated in three zonal bands showing how the bias changes with latitude. The bias is largest in the tropics. Nearly all cases suggest that the AIRS 2616cm^{-1} channel provides more accurate SST's than the AIRS 1231cm^{-1} channel, with smaller biases and standard deviations.

A three-way error analysis is carried out using co-locations of bulk AATSR, AIRS and buoy SST's. This gives enough information to enable the standard deviation of error of each observation type to be derived. Using AIRS 2616cm^{-1} SST's the AATSR observations are shown to have a very small error of 0.14K, whilst the buoy SST's have an error of 0.22K and the AIRS SST observations have an error of 0.41K. When using AIRS 1231cm^{-1} SST's the AIRS error is greater at 0.50K, showing that the 2616cm^{-1} channel provides more accurate SST's.

1. Introduction

In order to ensure the quality and consistency of the sea surface temperatures (SST) derived from satellite data, validation with other satellite instruments is essential. Validation of SST's derived from the Advanced Along-Track Scanning Radiometer (AATSR) has been carried out in the past using a variety of satellite instruments and insitu datasets. O'Carroll et al (2006a) performed a three-point error analysis between AATSR, the Advanced Microwave Scanning Radiometer (AMSR-E) and buoy observations. This method, which uses co-location of the three different observation types, enables the error of each observation type to be derived. Advanced Infra-Red Sounder (AIRS) SST's allow further validation possibilities.

This report presents a comparison of AATSR SST's with AIRS SST's and a three-point error analysis between AATSR, AIRS and Buoy measurements. As we already have a good idea of the accuracy of the AATSR instrument this will be an opportunity to validate AIRS with respect to AATSR and to provide another check that the AATSR instrument is still on track with providing SST's to the desired accuracy. The comparisons use mean monthly SST fields from each of the instruments and will concentrate on January 2006, April 2006 and June 2006. This is because a substantial amount of data is available for these months from all three data sources and they give a good cross section of the first half of 2006.

This report gives details on the data sources in section 2 and how the SST's are calculated in section 3. The results of the AATSR and AIRS comparison are in section 4 and the three-point AATSR, AIRS and buoy error analysis in section 5. The conclusions of this report are in section 6.

2. Data Sources

2.1 AATSR Instrument

The Advanced Along-Track Scanning Radiometer (AATSR) was launched as part of the European Space Agency's (ESA's) ENVISAT satellite in March 2002. AATSR has three infrared channels centred in atmospheric windows at 3.7μm, 11μm and 12μm. There are additional channels at visible and near-infrared wavelengths which are used for cloud detection. The instrument is designed to produce dual view sea surface temperature (SST) allowing for effective correction of atmospheric absorption and aerosol. It achieves this by having an inclined conical scanner which enables it to make observations from two different angles, nadir and forward (~55°) within a few minutes of each other. The instrument aims to provide data to derive SST to within 0.3K accuracy and with a long term stability of 0.1K. It continues the collection of data by Along Track Scanning Radiometers which started in 1991.

AATSR can "see" only the top few microns of the ocean. This gives a radiative skin SST which is cooler than the sub-skin temperature by 0.1K or more. The AATSR measurements used in this study are dual-view, and use all three infrared channels (D3). Night-time only data is used to avoid

problems associated with diurnal warming and solar contamination of the 3.7µm channel. Night-time is defined here as when the solar zenith angle is greater than 95°. For validation with other satellite instruments the skin SST is used. However for the three-point comparison with AIRS and buoy measurements, a bulk SST is derived using the cool skin model proposed by Fairall et al (1996). More information on the processing of skin to bulk SST's can be found in O'Carroll et al (2004) and O'Carroll et al (2006b). Figure 1 shows a skin SST map from AATSR for June 2006.

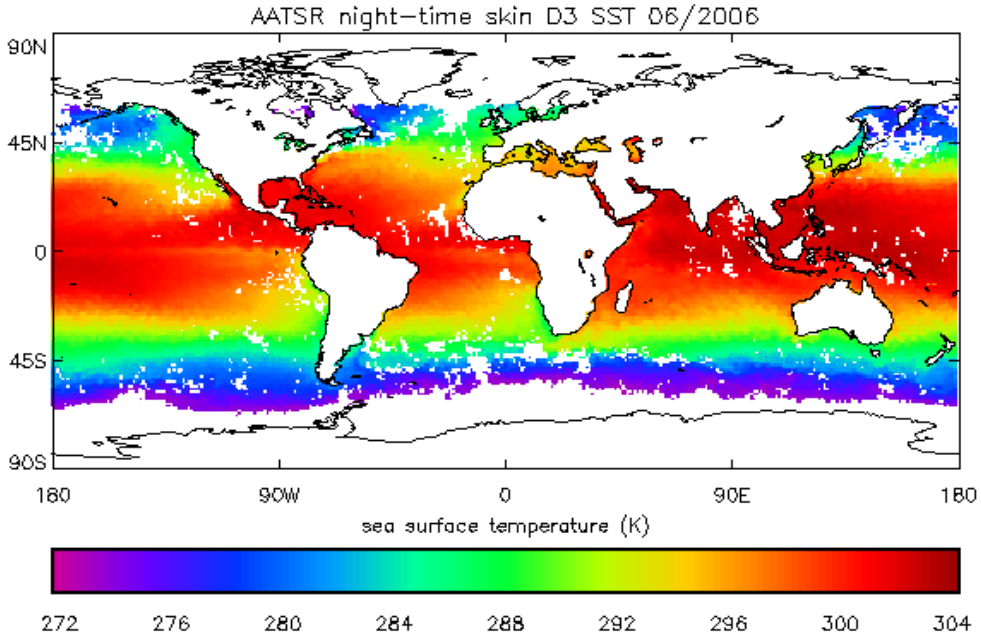

Figure 1. D3 Skin SST from AATSR for June 2006

2.2 AIRS Instrument

The Atmospheric Infrared Sounder (AIRS) is an infrared spectrometer that covers the 3.7-15.4 µm spectral range with 2378 spectral channels. It was launched as part of the National Aeronautics and Space Administration's (NASA's) AQUA satellite in May 2002. Being an Infra-red instrument AIRS, like AATSR, can only "see" the top few microns of the ocean and is unable to detect the surface through cloud. AIRS primary purpose is for atmospheric sounding applications. Each spectral channel on AIRS is much narrower than AATSR so it can "see" through the atmosphere between the absorption lines. In this study two AIRS SST's are calculated using information primarily from channel numbers 1291 and 2333 corresponding to 1231cm^{-1} and 2616cm^{-1} respectively. AIRS has a larger footprint than AATSR, with a diameter of 14km (compared to 1km for AATSR). More detail on the AIRS SST retrieval is in the methodology section. Figure 2 shows a map of SST from AIRS for June 2006.

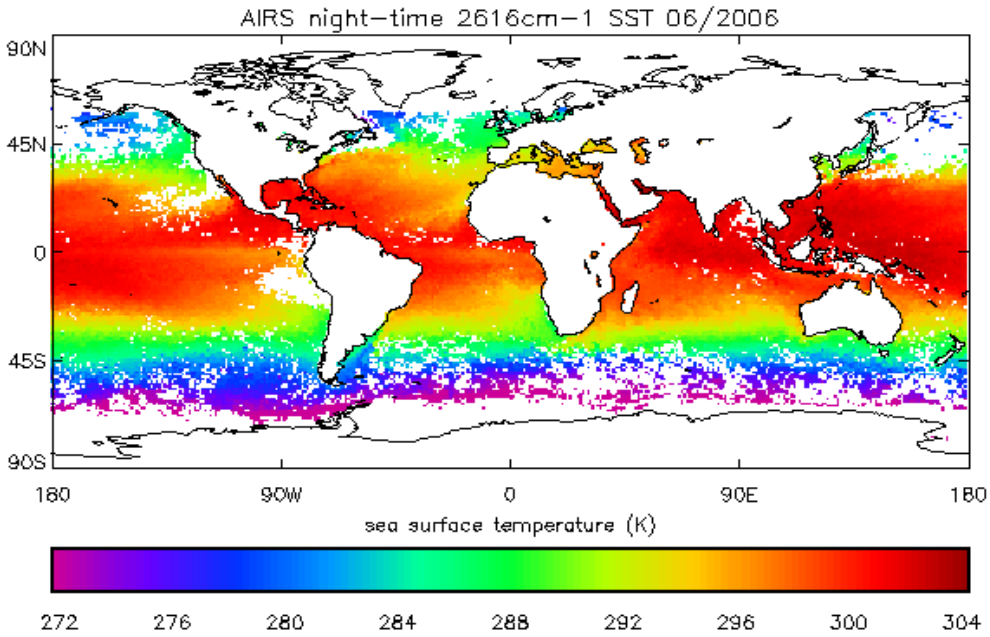

Figure 2. AIRS SST using 2616cm^{-1} channel for June 2006

2.3 AMSR-E Instrument

The Advanced Microwave Scanning Radiometer (AMSR-E) provided by the National Space Development Agency of Japan (NASDA) was launched along with AIRS on NASA's AQUA satellite. Global, daily version 5 AMSR-E SST products are retrieved from the Remote Sensing Systems (RSS) website http://www.ssmi.com. These have had a bias applied. More details on the product can be found on the RSS site. The microwave instrument has some key differences from the infra-red instruments. A major advantage is that it can view the surface through non-precipitating cloud giving SST in areas that the infra-red instruments cannot see. AMSR-E senses the sea surface to a depth of a few millimetres. The SST's derived from this are bias corrected and represent the temperature at a depth of roughly a metre while the SST's from the Infrared instruments represent the temperature of the top few microns.

2.4 Buoys

Global moored and drifting buoy SST measurements are obtained from the Global Telecommunications System. These are used in the three-point match-up statistics presented. The buoy SST's are co-located to the AATSR 10 arc minute cell within a 3 hour time window to provide an AATSR-buoy match-up dataset. This is then matched with AIRS observations to produce three-point statistics. Buoys measure an SST at around one metre depth below the surface. AATSR skin SST's are converted to bulk SST's, around one metre in depth, to be compared with buoys.

3. Methodology

3.1 AATSR SST

AATSR skin and bulk SST's are calculated from the AATSR "Meteo" product. This contains cloud-free, 10 arc-minute, spatially-averaged, top-of-atmosphere brightness temperatures measured in the instrument's two views

and three infra red channels and is received from ESA daily in near real time. A skin SST is present in the meteo product but the approach adopted here is to calculate skin SST from the brightness temperatures. To calculate this skin SST a set of coefficients are needed. Currently the ESA pre-launch coefficients are used. Once the coefficients, a_i, have been weighted according to swath-position and latitude the calculation of surface temperature is carried out by linear combination of the observed brightness temperatures, T, in the different channels (3.7, 11 and 12 μm) and views (N for nadir, F for forward views) multiplied by their individual regression coefficients. The calculation for D3 is outlined in equation 1.

$$T_S^{D,3} = a_0 + a_1 T_{11}^N + a_2 T_{12}^N + a_3 T_{3.7}^N + a_4 T_{11}^F + a_5 T_{12}^F + a_6 T_{3.7}^F \qquad (1)$$

In this study only night-time AATSR observations are used to reduce the effect of diurnal warming on the observations. The AATSR skin SST's are bias corrected before use. The bias correction is calculated by using the AATSR match-ups with buoys. This process involves converting the buoy SST's to a buoy "skin" SST using the Fairall model (Fairall et al, 1996). This buoy skin SST is then compared with the AATSR skin SST using only night-time match-ups where the time difference between the observations is less than 1 hour. The biases are determined from these comparisons using a 3-sigma standard deviation test to remove outliers. This gives the bias correction to be applied to the D3 AATSR skin SST's as -0.22K. This bias is thought to be due to a spectral leak in the AATSR 12μm channel. Bulk SST can then be calculated from the bias corrected skin SST's (O'Carroll et al, 2006b).

A number of cloud clearing tests are applied to the AATSR data. The pixel is flagged as cloudy if any one of the tests indicates the presence of cloud. The first cloud test applied, the gross cloud test, consists of comparing the 12um brightness temperature with a threshold value that is set to be lower than the brightness temperature expected from the surface. More detail on the cloud tests applied can be found in the AATSR product handbook (Birks, 2006) and in Závody et al (2000).

3.2 AIRS SST Retrieval

The AIRS radiances are downloaded in HDF format from NASA (ftp://g0dps01u.ecs.nasa.gov/AIRS/AIRXBCAL.003) and extracted along with other relevant fields. Two SST's are calculated. These are sst1231r5 (hereafter referred to as AIRS.sst1231) and sst2616v24s (hereafter referred to as AIRS.sst2616). These are used because 2616.3cm^{-1} is the most transparent channel in the AIRS spectrum and 1231.3cm^{-1} is the next best window channel (Aumann et al, 2006).

Unlike the AATSR retrieval which uses a combination of channels and views, the AIRS SST retrievals use radiances from the window channels and then apply a small correction due to residual water vapour continuum absorption with a nearby channel which is in a water vapour absorption line.

AIRS.sst1231 is the sea surface temperature assuming an emissivity, e=0.98 under cloud-free conditions (Gohlke, 2006). It is primarily based on the 1231.3cm^{-1} channel but also uses the difference between the 1231.3cm^{-1} and 1227.7cm^{-1} channel for a water vapour correction. This SST is an existing product in the HDF file so can be directly extracted and used. The algorithm to calculate it from brightness temperatures is given in the AIRS Clear Match Functional and Software Design Specification (Gohlke, 2006) and is shown in equation 2.

$$sst1231r5 = bt_1231 + 0.28 + (1.2 * q3) + (0.2962 * q3^2) + \frac{1.0489}{\cos(satzen)} \qquad (2)$$

Where $q3 = bt_1231 - bt_1227$, bt_1231 is the brightness temperature of the 1231cm^{-1} channel, bt_1227 is the brightness temperature of the 1227.7cm^{-1} channel and satzen is the satellite zenith angle in degrees.

AIRS.sst2616 is not included in the HDF file. It has to be calculated from the radiances and satellite zenith angle. The window channel at 2616.3 cm^{-1} and the water sensitive channel at 2607.8 cm^{-1} are used for the derivation of AIRS.sst2616. The equivalent blackbody brightness temperatures are calculated from the radiances using the standard Planck Formulae. Then the emissivity correction is calculated in the radiance domain. The scan angle and wind speed dependant seawater emissivity from Masuda et al (1988) is used. The emissivity, e, is based on a numerical fit to the Masuda data as a function of scan angle at 5ms^{-1} wind speed. Data with satellite zenith angles greater than 35° are eliminated to avoid large uncertainties (Aumann et al, 2006). The remaining emissivity corrections are set up as an array matching the 2616cm^{-1} brightness temperature. This is then filled with the emissivity corrections, as represented by equations 3a) and 3b).

for satzen ≤ 25°: e2616=1.0 (3a)

for satzen > 25°: $e2616 = \left(\cos\left(\frac{(satzen - 25) * 0.6}{57.3} \right) \right)^{0.4}$ (3b)

Then the atmospheric transmission correction is calculated in the brightness temperature domain. This is used to correct for water vapour absorption in the atmosphere. With an increase in water vapour in the path there is an increase in the difference between the brightness temperature at 2616.3cm-1 and 2607.8cm-1. We define q2= bt_2616 – bt_2607 where bt_2616 and bt_2607 are the observed brightness temperatures at 2616 and 2607 cm^{-1} respectively. Aumann et al (2006) have plotted the transmission loss due to atmospheric absorption for 24 profiles at six slant paths from nadir to 50° as a function of q2 to which a quadratic fit has been applied. The calculation of q2 from the spectrum then gives the required atmospheric transmission correction. This can be achieved using equation 4.

$$a2616 = 0.109 + (0.0432 * q2) + (0.00689 * q2^2) \qquad (4)$$

The emissivity correction and atmospheric transmission correction are then used in equation 5 to calculate sst2616 used in this report.

$$sst2616v24s = btemp(2616, planck(2616, bt_2616 + a2616)/(0.976 * e2616)) \quad (5)$$

Further details of the AIRS.sst2616 algorithm (Aumann et al, 2006) are given in the Matlab code in Appendix A.

It is important to note that when comparing AIRS SST's with SST's from AATSR and AMSR-E that the AIRS SST is computed using a simple radiative transfer algorithm whereas the other satellite instruments SST's have been computed using complex regression algorithms and have then been bias corrected. For AIRS SST's no bias or tuning correction of any kind has been applied.

The cloud filter used for AIRS uses a spatial coherence parameter, cx2616, defined as the difference between the maximum and minimum brightness temperatures at 2616.3cm-1 of a 3x3 group. If cx2616 is below the threshold of 1.2K, the centre footprint is defined as cloud free. As an additional test this was re-filtered at cx2616<0.5, which found a residual 0.2K cold bias due to cloud contamination. A low stratus test is also carried out which makes use of the fact that the atmosphere above stratus clouds is very dry and this can be detected by the water vapour sensitive channels in the AIRS spectrum (Aumann et al, 2006).

4. Comparison of AATSR minus AIRS

Both the AATSR bias corrected skin and AIRS SST's are gridded into a 'PP' file. PP is a record-based, binary, Met Office proprietary format. In this case the data is gridded with one degree resolution. Where there is more than one SST observation in a degree grid box, the mean SST for that grid box is taken. This report looks at comparing monthly data so the daily PP files are concatenated into monthly PP files. The monthly PP files from the different instruments can then be compared by subtracting the AIRS SST from the AATSR SST to give the difference between AATSR and AIRS derived SST's. This is carried out with both of the AIRS SST's (AIRS.sst1231 and AIRS.sst2616) separately and gives two AIRS comparisons with AATSR. In addition to the Global analysis, statistics are also collected in three latitude bands, latitudes greater than 30°N (hereafter referred to as the Northern band), latitudes between 30°N and 30°S (hereafter referred to as the Tropics) and latitudes less than 30°S (hereafter referred to as the Southern band).

As a useful indicator of how well this process is performing a monthly AMSR-E SST PP file is also created. AATSR SST minus AMSR-E SST and AIRS SST minus AMSR-E SST statistics can then be calculated and used as a check that the AATSR minus AIRS statistics are as one would expect as well as generating interesting results in their own right.

All these statistics are treated with the 3-sigma standard deviation test which only uses results within three times the standard deviation from the mean. This discards any extreme outliers from the statistics.

Figures 3 and 4 and 5 show example anomaly plots of AATSR SST minus AIRS SST, AATSR SST minus AMSR-E SST and AIRS SST minus AMSR-E SST respectively.

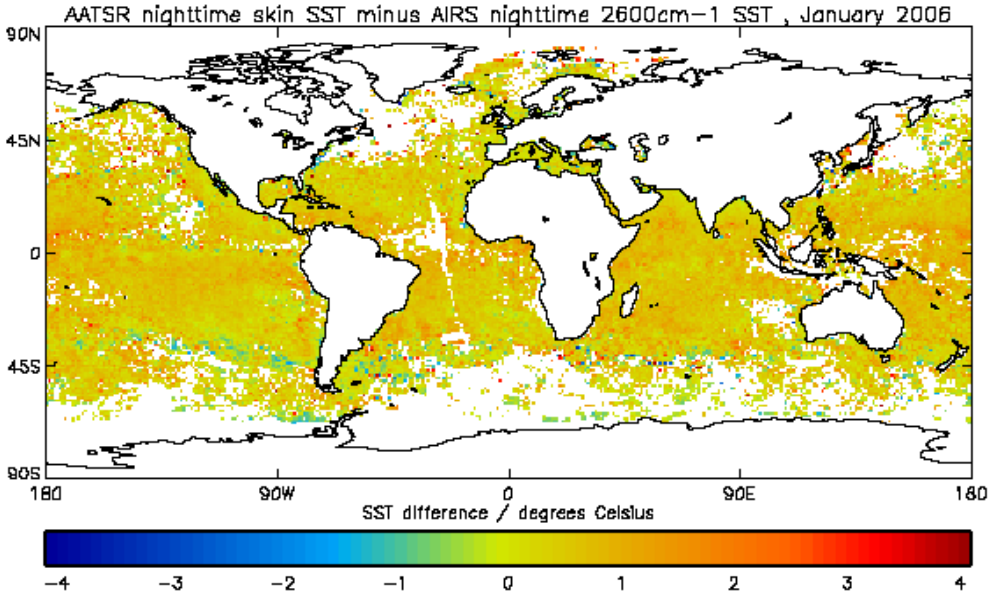

Figure 3. AATSR SST minus AIRS 2616cm^{-1} SST for January 2006

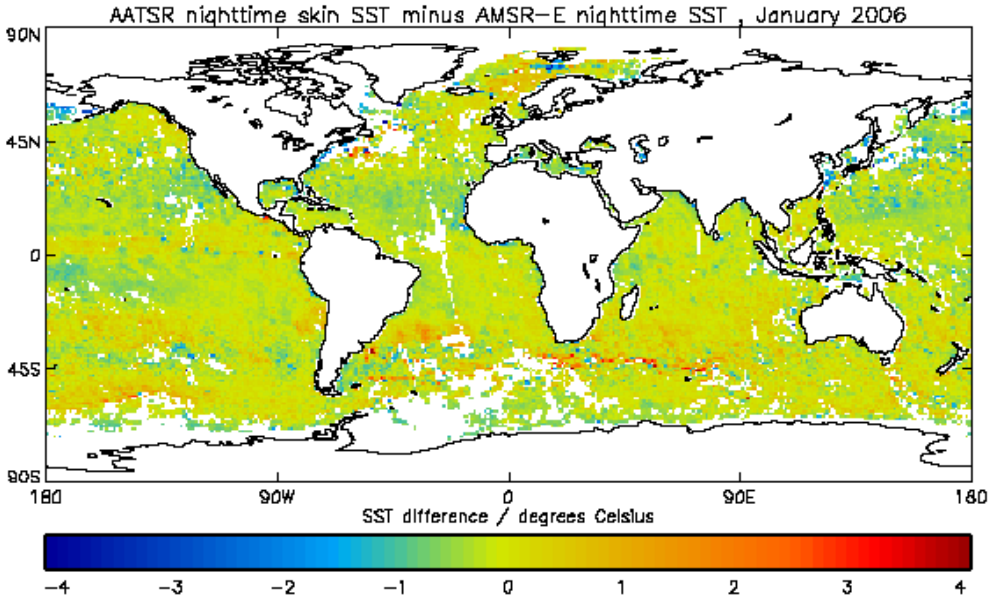

Figure 4. AATSR SST minus AMSR-E SST for January 2006.

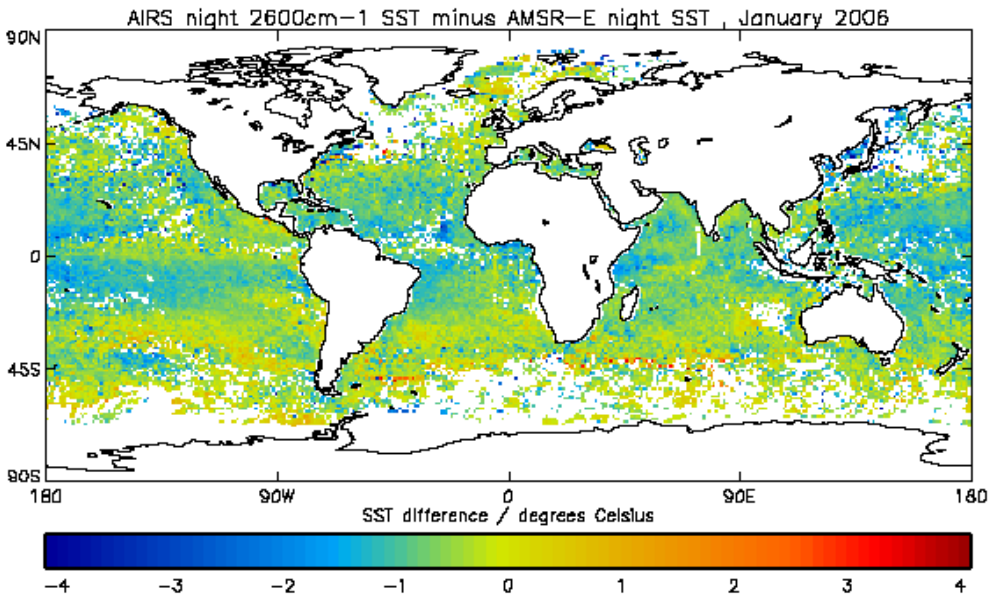

Figure 5. AIRS.sst2616 minus AMSR-E SST for January 2006.

From these three figures it is possible to see that AATSR minus AIRS has a positive bias, AATSR minus AMSR-E has a neutral or slightly negative bias and AIRS minus AMSR-E has a negative bias. It is also interesting to note that AIRS has less coverage than AATSR and that large SST differences occur in the same places in all three plots.

The comparison between the three plots can be studied further by looking at the statistics. Table 1 shows the statistics from the AATSR SST minus AIRS SST.

Overall AATSR minus AIRS gives a positive bias. This means AIRS is giving colder SST's than AATSR. Globally this bias is in the region of 0.5 K. The global standard deviation is in the region of 0.6K. The bias is partly due to the different cloud detection schemes applied to the data from each instrument. Some of the difference can also be attributed to the different retrieval algorithms for the two datasets. The AIRS dataset uses individual narrow channels that can see between absorption lines, while the AATSR SST dataset uses a combination of three wider channels and two coincident views. There is also some contribution from the slightly different absorption characteristics of the atmospheric windows that the different instruments use.

A difference between the biases and standard deviations is evident when using the two different AIRS channels. The bias between AATSR and AIRS is larger when using the 1231cm^{-1} AIRS SST than when using the 2616cm^{-1} AIRS SST. This is particularly seen in the tropics where the effects of water vapour are greatest, and this effect is diluted by the dryer high latitude air in the global statistics. For the 3 months studied the difference in bias between the channels in the tropics is between 0.11 and 0.14 K. The standard deviation is also larger by around 0.1K in the tropics when using AIRS 1231cm^{-1}. Both the smaller bias and the smaller standard deviation show that

AIRS channel 2616cm^{-1} is better for SST measurements than channel 1231cm^{-1}.

a) January 2006

Area	**AIRS Channel/cm^{-1}**		**Mean bias / K**		**Standard Deviation /K**		**Number of Matches**	
Global	1231	2616	0.51	0.49	0.62	0.52	25363	25365
>30N	1231	2616	0.37	0.36	0.72	0.65	3567	3564
30S-30N	1231	2616	0.71	0.60	0.51	0.40	14346	14384
<30S	1231	2616	0.19	0.32	0.62	0.59	7408	7404

b) April 2006

Area	**AIRS Channel/cm^{-1}**		**Mean bias / K**		**Standard Deviation /K**		**Number of Matches**	
Global	1231	2616	0.59	0.53	0.61	0.51	24677	24621
>30N	1231	2616	0.43	0.40	0.65	0.60	3719	3718
30S-30N	1231	2616	0.78	0.64	0.48	0.38	14425	14406
<30S	1231	2616	0.26	0.37	0.70	0.66	6478	6482

c) June 2006

Area	**AIRS Channel/cm^{-1}**		**Mean bias / K**		**Standard Deviation /K**		**Number of Matches**	
Global	1231	2616	0.60	0.55	0.64	0.58	24568	24553
>30N	1231	2616	0.44	0.38	0.96	0.93	2965	2959
30S-30N	1231	2616	0.70	0.58	0.49	0.43	14601	14592
<30S	1231	2616	0.49	0.55	0.81	0.74	7076	7080

Table 1. Statistics for AATSR (bias-corrected, night-time) D3 skin SST minus AIRS night-time SST for a) January 2006, b) April 2006 and c) June 2006. The 3-sigma test has been applied in all cases.

Saunders (1989) discusses the transmittance at various frequencies and the attribution of this to various gases. In both these windows water vapour is the main absorber, with other gases contributing little to the absorption. Globally averaged the effect of water vapour absorption is greater in the 1231cm^{-1} channel than the 2616cm^{-1} channel making the latter more transparent to radiation, therefore giving a more accurate SST. The difference is largest for high water vapour columns in the tropics.

When using either AIRS channel the bias increases from January to June. With AIRS 1231cm^{-1} the increase from January to June is 0.09K and with AIRS 2616cm^{-1} it is 0.06K. The standard deviation largely follows the same pattern at higher latitudes, except for dipping slightly in April in the Northern band, however in the tropics band shows less of a change between the seasons and has lower standard deviations. The pattern seen here is due to the (cloud free) atmosphere containing more water vapour in the summer than the winter due to increased evaporation from the surface. In the tropics band there is less difference between the seasons.

The three latitude bands, Northern (>30N), Tropical (30S-30N) and Southern (<30S) give an idea of how the bias and standard deviation vary over the globe. Between 12% and 15% of match-ups occur in the Northern band, 57%

to 59% in the Tropics band and 26% to 29% in the Southern band. There is an asymmetry between the Southern and Northern band. Within the month, the winter hemisphere has a higher bias than the summer hemisphere. This could be due to cloud contamination of the AIRS data, as the winter hemisphere will be cloudier than the summer hemisphere. Aumann et al (2006) shows some evidence of cloud contamination of the AIRS SST. They show that there is a 0.6K cold bias for the ±30° tropical oceans relative to the real-time global sea surface temperature (RTGSST) analysis produced by the National Centres for Environmental Prediction (NCEP). Based on surface observations by MAERI, a ship-mounted radiometer, a 0.2K cold skin bias is expected relative to buoys and a ±0.2K diurnal cycle relative to the RTGSST. This accounts for all but 0.2K of the observed cold bias, which is due to residual cloud contamination. This cloud contamination has a mean value of 0.2K and standard deviation of 0.2K, assuming it follows a Gaussian distribution.

For the AIRS 1231cm^{-1} channel, water vapour continuum is the principle absorber varying from 60% transmittance for a moist tropical atmosphere to 97% for a dry polar atmosphere. For the AIRS 2616cm^{-1} channel there is much less absorption with the transmittance being 96% for a moist tropical atmosphere and 99% for a dry polar atmosphere (Roger Saunders, personal communication). The schematic diagram, Figure 6, shows how transmittance changes.

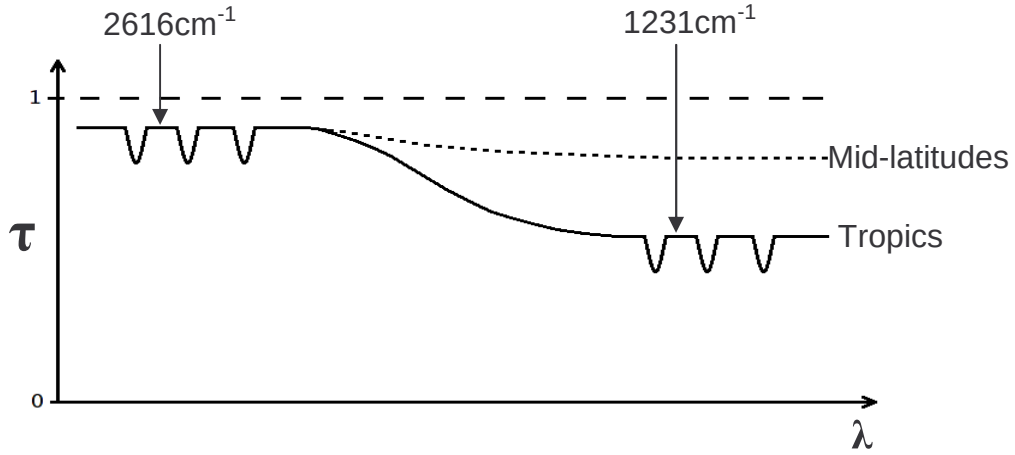

Figure 6. Schematic diagram showing atmospheric transmittance changes between different AIRS channels (Roger Saunders, personal communication).

This explains some of the patterns seen in the statistics. A change in the water vapour continuum absorption, rather than the smaller absorption fluctuations, is the cause of the difference between the channels as both channels are narrow enough to see between the absorption lines. In the tropics the bias is much higher when using the 1231cm^{-1} AIRS SST than when using the 2616cm^{-1} AIRS SST. In the northern band this difference is much smaller, as figure 6 suggests, although the southern band has a higher bias when using the 2616cm^{-1} AIRS SST. The standard deviation is higher when using 1231 cm^{-1} AIRS SST, for all regions.

Within each AIRS channel the tropical atmosphere is more consistent in its state than the Northern and Southern band atmospheres which are very changeable. This may explain the smaller standard deviation in the tropics. Also the cloud clearing problems increase at higher latitudes so this may increase the standard deviation in these regions.

A very high standard deviation occurs in the Northern band, and to a lesser extent in the Southern band, in June for both channels. Some investigation of the statistics has shown that the high standard deviations are mostly occurring in the North Pacific area and to a lesser extent off the coast of Canada. Figure 7 shows where this effect is happening, mostly off the coasts of Newfoundland and Japan on the edge of the cloudy areas. In these areas there is a cold AIRS bias. Off the east coast of Asia and North America there are slow moving fronts of very warm air (during the summer) and very cold air (during the winter) pushing eastward, which creates unusual clear conditions before the inevitable low clouds appear. The low clouds are difficult to detect with the AIRS day/night cloud filter algorithm, but may well be picked up by the AATSR cloud filter. However due to the difference in size of footprint between AIRS (14km diameter) and AATSR (1km diameter), some cloud contamination can still occur for AIRS. The smaller AATSR footprint can identify clear data better. It is also possible that AATSR is less sensitive to certain low clouds which are not caught by the AIRS cloud filter. When the cloud contamination becomes significant, the AIRS SST has a cold bias. This pattern is also seen in the AIRS SST minus AMSR-E SST statistics and plots for this month.

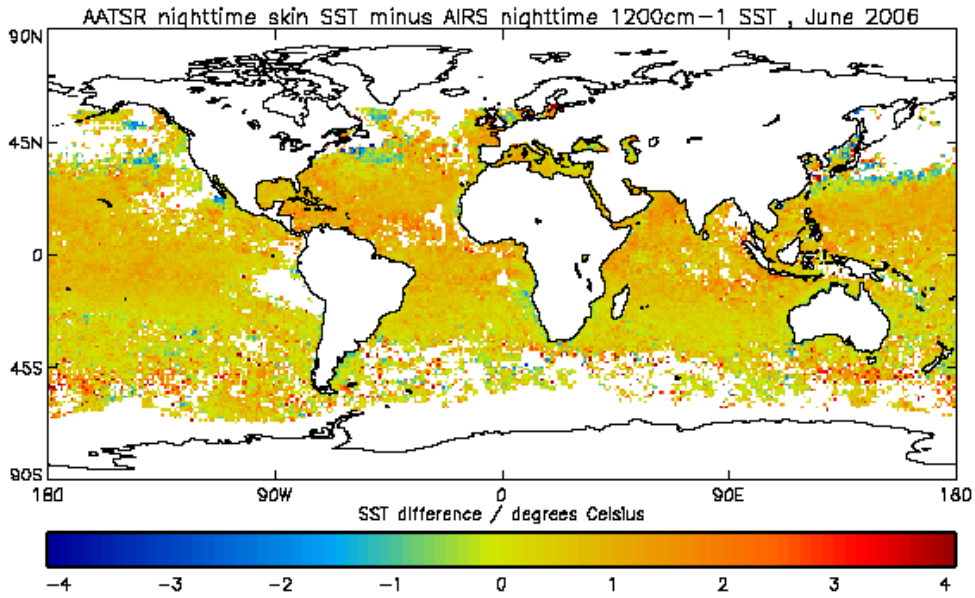

Figure 7. AATSR SST minus AIRS 1231cm^{-1} SST plot showing areas of cold AIRS bias at the Northern edge of the data

The next stage of this report looks at using the AMSR-E SST compared with both AATSR SST and AIRS SST separately to check the validity of the AATSR minus AIRS statistics shown above. Bias corrected AATSR D3 skin SST minus AMSR-E SST is shown in Table 2. These, and the AIRS SST

minus AMSR-E SST, are carried out for the same three months in 2006 as the AATSR minus AIRS. In all cases night-time only data is used and the 3-sigma test is used to remove any extreme outliers.

a) January 2006

Area	**Mean bias / K**	**Standard Deviation /K**	**Number of Matches**
Global	-0.14	0.38	28661
>30N	-0.23	0.49	4322
30S-30N	-0.18	0.30	14077
<30S	-0.04	0.43	10286

b) April 2006

Area	**Mean bias / K**	**Standard Deviation /K**	**Number of Matches**
Global	-0.07	0.37	27599
>30N	-0.19	0.45	3986
30S-30N	-0.07	0.28	14090
<30S	-0.01	0.44	9512

c) June 2006

Area	**Mean bias / K**	**Standard Deviation /K**	**Number of Matches**
Global	-0.06	0.38	27028
>30N	-0.08	0.64	3670
30S-30N	-0.13	0.27	14208
<30S	0.06	0.42	9169

Table 2. AATSR skin SST minus AMSR-E SST statistics for a) January 2006, b) April 2006 and c) June 2006.

The biases are small and negative. This means that AMSR-E SST's are slightly warmer than AATSR skin SST's. This is as expected because AMSR-E SST's have had a bias correction applied based on co-locating buoys with the first year of AMSR-E data then applying this bias correction to all the data giving an SST representative of the temperature at roughly a metre below the surface (Chelle Gentemann, personal communication). AATSR SST's represent the temperature in the top few microns. The temperature in this layer is lower than the temperature below this layer. This is due to the skin effect. The zone with the highest bias is most often the Northern band whereas for AATSR minus AIRS it is the tropics band. The standard deviations are slightly smaller than the standard deviations from AATSR minus AIRS, but follow the same latitudinal pattern.

Table 3. Shows the results of AIRS SST minus AMSR-E SST for the three months of interest in 2006.

a) January 2006

Area	AIRS Channel /cm^{-1}		Mean bias /K		Standard Deviation /K		Number of Matches	
Global	1231	2616	-0.66	-0.64	0.66	0.54	25237	25228
>30N	1231	2616	-0.70	-0.69	0.78	0.72	3546	3552
30S-30N	1231	2616	-0.90	-0.79	0.54	0.44	13842	13877
<30S	1231	2616	-0.21	-0.34	0.57	0.54	7826	7820

b) April 2006

Area	AIRS Channel /cm^{-1}		Mean bias /K		Standard Deviation /K		Number of Matches	
Global	1231	2616	-0.68	-0.63	0.64	0.55	25291	25244
>30N	1231	2616	-0.65	-0.62	0.65	0.62	3811	3815
30S-30N	1231	2616	-0.85	-0.71	0.46	0.38	13832	13818
<30S	1231	2616	-0.34	-0.46	0.78	0.74	7630	7614

c) June 2006

Area	AIRS Channel /cm^{-1}		Mean bias /K		Standard Deviation /K		Number of Matches	
Global	1231	2616	-0.70	-0.65	0.66	0.59	24372	24368
>30N	1231	2616	-0.51	-0.46	0.86	0.83	2657	2657
30S-30N	1231	2616	-0.84	-0.72	0.46	0.41	13833	13824
<30S	1231	2616	-0.53	-0.59	0.85	0.78	7913	7917

Table 3. AIRS SST minus AMSR-E SST statistics for a) January 2006, b) April 2006 and c) June 2006

AIRS SST's are consistently colder than the AMSR-E SST's. AMSR-E SST's are bias corrected so give the temperature at roughly a metre below the surface, while AIRS measures the temperature in the first few microns. Due to evaporation from the surface this temperature is about 0.2 K colder than what AMSR-E measures. After this correction AIRS still reads around 0.4K colder than AMSR-E. This is partly due to residual cloud contamination in the AIRS data. (George Aumann, Personal Communication). The standard deviations are similar in magnitude and pattern to the AATSR minus AIRS standard deviations.

It is possible to use the AATSR minus AMSR-E bias and AIRS minus AMSR-E bias to produce a projected AATSR minus AIRS bias, as (AATSR-AIRS)=(AATSR-AMSR-E)-(AIRS-AMSR-E), which can then be compared with the AATSR minus AIRS shown in Table 1. This has shown the differences to be very small demonstrating that our method for calculating AATSR minus AIRS is robust.

5. Three-point error analysis – AATSR, AIRS and Buoys

An extension to the three-point error analysis carried out by O'Carroll et al (2006a) is presented in this section. In that study AATSR, AMSR-E and Buoy SST's were co-located providing a mean and standard deviation of the difference between each of the three observation sets. From this enough information can be gained to enable the error of each observation to be derived. Assuming the errors in the three observation types are uncorrelated, the error is calculated using equation (6). The appendices of O'Carroll et al (2006a) give more detail on the calculation and a discussion of the validity of assuming the errors are uncorrelated.

$$\sigma_1=\{½(V_{12}+V_{31}-V_{23})\}^{½}$$
$$\sigma_2=\{½(V_{23}+V_{12}-V_{31})\}^{½} \qquad (6)$$
$$\sigma_3=\{½(V_{31}+V_{23}-V_{12})\}^{½}$$

Where σ_i is the estimated error for observation type i (where i = 1,2, or 3) and V_{ij} is the variance of the difference between observation types i and j.

The three-point match-up uses an existing global AATSR and buoy match-up file. This contains match-ups using bulk adjusted AATSR SST's to provide better comparisons with the buoy SST's. The AATSR SST's have also been bias corrected. Match-ups are only selected if they occurred during the night and if the AATSR and Buoy measurements were taken within 3 hours of each other. Both drifting and moored buoy SST's are used. The AIRS SST's, which are not bulk adjusted, are then matched with the remaining AATSR-buoy match-ups and the statistics are calculated. The 3-sigma standard deviation test is applied to filter out any extreme outliers. Future work could involve bulk adjusting the AIRS SST's using the Fairall model to convert to bulk to provide a better comparison with AATSR bulk SST and buoy SST.

The biases and standard deviations calculated using this method shown in Table 4 are for a mean of the three months in 2006 that this report focuses on.

Comparison	**AIRS Channel /cm^{-1}**		**Mean bias /K**		**Standard Deviation /K**		**Number of Matches**	
AATSR-AIRS	1231	2616	0.60	0.56	0.52	0.43	267	268
Buoy-AIRS	1231	2616	0.61	0.56	0.55	0.46	267	268
AATSR-Buoy	1231	2616	-0.01	-0.01	0.26	0.26	267	268

Table 4. Biases and Standard deviations from three-point, AATSR, AIRS, Buoy Match-ups for a mean of three months in 2006 (January, April and June).

AIRS SST is cooler than bulk AATSR and buoy SST by about 0.6 Kelvin. We would expect this because AIRS observes the temperature of the ocean skin, the top few microns, which is generally a few tenths of a Kelvin cooler than just below the ocean skin. The AATSR skin SST measures the same part of the ocean skin and a comparison with AIRS SST elsewhere in this report gave a bias of around 0.4 to 0.5 K. For the three-point match-up the AATSR

SST has been adjusted to give a bulk SST to be directly comparable with buoy SST. Because of this adjustment we would expect the AATSR SST to become warmer still by a few tenths of a Kelvin. This would increase the bias between AATSR and AIRS SST which explains why the bias is larger in this comparison. Because of the bulk adjustment of AATSR SST and the bias correction applied to it, the AATSR SST minus buoy SST gives a very small bias, hundredths of a degree and a small standard deviation, only a few tenths of a degree. There is a larger bias and standard deviation when using AIRS.sst1231 than AIRS.sst2616. This pattern agrees with the AATSR-AIRS comparison shown previously in this report and is explained by differences in the water vapour continuum absorption between the two channels as shown in figure 6.

When comparing these results to the results obtained by O'Carroll et al, 2006a, shown in Table 5, the biases cannot be directly compared as the AMSR-E SST's in that study are bulk corrected, however the standard deviations show a similar pattern but are slightly lower in the O'Carroll three-point match-ups. This may be due to the larger number of matches.

Comparison	**Mean bias / K**	**Standard Deviation /K**	**Number of Matches**
AATSR-AMSR-E	0.02	0.45	2970
Buoy-AMSR-E	0.02	0.48	2970
AATSR-Buoy	0.00	0.28	2970

Table 5. Biases and standard deviations for all 2003 from three-point AATSR, Buoy, AMSR-E paper (From O'Carroll et al, 2006a, Table 2)

An error analysis is carried out using the method described at the beginning of section 5 (equation 6). The results of this analysis for the three month mean shown in Table 6. give very similar results to those in the three-point AATSR, Buoy, AMSR-E paper (O'Carroll et al, 2006a) which show an error of 0.16 for the AATSR bulk SST, 0.42 for the AMSR-E SST and 0.23 on the buoy SST. The error is smallest for AATSR. Buoys have the next smallest error and AIRS has the largest error. The errors of the AIRS SST are comparable with the error of AMSR-E SST in the O'Carroll paper (2006a). The AIRS SST errors are smaller when using the 2616cm^{-1} channel than when using the 1231cm^{-1} channel. This supports the earlier AATSR-AIRS comparison which gives a smaller bias and standard deviation using the 1261cm^{-1} channel, suggesting it to be more accurate for calculating SST.

			Derived standard deviation of error for each observation type/ K					
	AIRS Channel/ cm^{-1}		**AATSR bulk (D3) SST**		**AIRS (Skin) SST**		**Buoy SST**	
3-month Mean	1231	2616	0.13	0.14	0.50	0.41	0.22	0.22

Table 6. Error Analysis using three-point match-up statistics.

6. Conclusions

AIRS gives a cooler SST than AATSR by around 0.5K. This may be due to residual cloud contamination of the AIRS data and residual atmospheric absorption effects. Both the two-point and three-point comparisons using AIRS suggest that the 2616cm^{-1} channel provides more accurate SST's with a smaller bias and standard deviation, particularly in the Tropics. This can be attributed to much lower water vapour continuum absorption at 2616cm^{-1} than at 1231cm^{-1}. There is an asymmetry between the Southern and Northern band. The Northern band has a larger bias than the Southern band in the Northern hemisphere winter and the Southern band has a larger bias than the Northern band in the Southern Hemisphere winter. This may be due to greater cloud cover in the winter months.

The three-point comparison involving AATSR, AIRS and buoys also suggests that AIRS gives a cooler SST than AATSR by about 0.5K. This method also gives an error for each data source. Using the AIRS 2616cm^{-1} channel, AATSR SST has the smallest error, 0.14K, followed by buoys with an error of 0.22K and AIRS 2616 SST has the largest error, 0.41K. The errors derived for AIRS 1231cm^{-1} are higher at 0.50K. These errors are very similar to the errors of the three-point comparison using AATSR, AMSR-E and Buoys carried out by O'Carroll et al (2006a). The error of AIRS using the 2616cm^{-1} channel is smaller than the error using the 1231cm^{-1} channel agreeing with the implication that AIRS 2616 cm^{-1} channel is better for estimating SST.

The AIRS SST products used in this report are simple, single channel retrievals. A more accurate method for AIRS would be to create an SST product that uses multiple channels and is optimised for different atmospheres. It is also believed that AIRS suffers more residual cloud contamination with its 15km field of view compared to AATSR's 1km field of view.

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Appendix 1
Matlab code for calculation of AIRS.sst2616 from brightness temperatures.

```
%Define C1 and C2
C1=0.000011910427;
C2=1.4387752;
% Calculate the 2616 cm-1 brightness temperature
bt2616s=(2616.4*C2)./(log(1+((2616.4.^3*C1)./radiances_values(:,1))));
% Calculate the 2616 cm-1 brightness temperature
bt2607s=(2607.8*C2)./(log(1+((2607.8.^3*C1)./radiances_values(:,2))));
% sst2616v24s
% The satzen is the array of the local satellite zenith angle in degrees.
% First we set up the Masuda emissivity as an array matching bt2616s.
e2616=ones(size(bt2616s));
v25=find(abs(satzen_values)>25);
e2616(v25)=(cos((abs(satzen_values(v25))-25).*0.6./57.3)).^0.4;
% Masuda v=5 m/sec
% Calculate the transmission correction for e=1.0 in temperature domain
% the coefficients are based on Jan2003 RTA   trained on 24 profiles at
% sza=[0,10,20,20,40,50].
q2=bt2616s-bt2607s;
% bt2616 = channel 2333 brightness temperature (2616.4 cm-1)
% bt2607 = channel 2325 brightness temperature (2607.8 cm-1)
a2616=0.109+0.0432.*q2+0.00689.*(q2.^2);
% the emissivity correction is done in radiance domain
% sst2616v24s=btemp(2616,planck(2616,bt2616s+a2616)./(0.976*e2616));
% emissivity corrected radiance(ecr)
E=(C2*2616.4)./(bt2616s+a2616);
rad=((2616.4.^3)*C1)./((exp(E))-1);
ecr=rad./(0.976*(e2616));
%final SST calcuation
sst2616v24s=(2616.4*C2)./(log(1+((2616.4.^3*C1)./ecr)));
```